

CNS Institute for Physics Teachers

Title:	Physics on an Electric Guitar
Original: Revision:	13 October 2006 24 June 2008
Author:	Jim Overhiser and Luke Donev
Appropriate Level:	Regents Physics
Abstract:	The guitar is one of the most common instruments in contemporary music. There are several aspects of the guitar that can be used to teach basic physics concepts; this lab focuses on magnetic pickups in an electric guitar. Students are led through a series of explorations to build experience with basic concepts in magnetism and electromagnetism. At the end they are asked to put these concepts together to explain how an electric guitar works.
Time Required:	Two 40 minutes periods
NY Standards Met:	4.1 j Energy may be stored in electric or magnetic fields. This energy may be transferred through conductors or space and may be converted to other forms of energy. 4.1 k Moving electric charges produce magnetic fields. The relative motion between a conductor and a magnetic field may produce a potential difference (voltage) in a conductor.
Special Notes:	Physics on an Electric Guitar is available as a kit from the CIPT Equipment Lending Library, www.cns.cornell.edu/cipt/ .

Behavioral Objectives:

Upon completion of this lab, a student should be able to:

- explain that an electric current generates a magnetic field.
- explain that a changing magnetic field induces an electric current in a nearby closed loop of wire.
- explain and demonstrate how ferromagnetic materials can become magnetized in the presence of a magnetic field.
- apply concepts of magnetism and electromagnetism to explain how a magnetic pickup on an electric guitar functions.
- explain how a loudspeaker works.

Class Time Required: Two 40-minute periods

Teacher Preparation Time: 5-10 minutes to set out kits and materials

Materials Needed: Kits available on loan from the CIPT lending library at www.cns.cornell.edu/cipt/. List of materials available on CIPT web site.

Assumed Prior Knowledge of Students:

- Basic electricity concepts
 - Definition of electrical current
 - Current flows only in a closed loop
- Basic magnetism concepts
 - Definition of N-S poles
 - Sketching magnetic fields
- Sound waves are variations in air pressure that can be caused by vibrating objects

Background Information for Teachers:

How magnetic pickups work

At the core of magnetic pickups are magnets. Each magnet is oriented so that an imaginary line through the north and south poles will intersect with the string above it. A thin copper wire coiled around the magnet so that the axis of the coil aligns with the N-S axis of the magnet.

The basic physics behind pickup is Faraday's Law of Induction. It states that a changing magnetic field can cause an electromotive force in a nearby wire. An electromotive force will be created as long as the wire is not parallel to the direction of the changing magnetic field. If the wire is a closed circuit or loop, then a current will flow. (See "Faraday's law of induction" in www.wikipedia.com for the full mathematical description.)

Since Faraday's Law states a changing magnetic field makes an electric current, how does the magnetic field from the fixed permanent magnets of the pickup help? That's where the guitar string comes into play. The string is made of nickel and steel (iron and carbon), materials that are ferromagnetic. The magnetic field from the permanent magnet in the pickup causes the string to become magnetized, or to become a magnet itself. When the magnetized string vibrates, it creates a changing magnetic field above the

pickup coil. This, in turn, makes a current flow (in the coil) that tracks the vibration of the string, and we have a working pickup!

Vibrating Strings

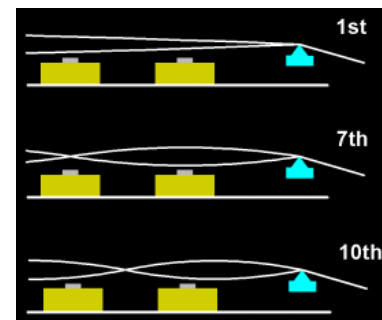
Understanding a vibrating string helps to understand how pickups sound. The diagram to the right shows a string vibrating over a pickup, viewed end-on. When you pluck a string, the string does not vibrate in a plane (red line), but in any number of planes, or circles (green), or ellipses (white). In fact, the ellipses can even rotate around their center as the note decays. This means that what you hear depends on how you pick the string, a phenomenon familiar to guitarists.



Harmonics

When you pluck a string it vibrates in the fundamental, second harmonic, third, fourth, etc., all at the same time. However, the pickup only detects string vibration when the string is vibrating near the pickup. It ignores the tones that have a node where the pickup is positioned. This has the effect of filtering the tones on the string.

On many electric guitars, two pickups are used on each string (see diagram to the right). Pickups are usually mounted close to the bridge, so each one is seeing the fundamental in some measure. That is, the string is moving either toward or away from all the pickups at the same time. When the signals coming out of the two pickups are added together, the fundamental has a strong signal.



For the seventh harmonic, the pickup on the right is at an antinode, getting a lot of signal, and the pickup on the left is at a node, putting out little signal. When the signals are added together, this harmonic comes across relatively strong.

For the tenth harmonic, the pickup on the right has the string moving away from it when the other pickup has the string moving toward it. This causes the signals from the pickups to cancel, so this harmonic is reduced in volume.

The distance between the pickups affects which harmonics will add and which will cancel. For example, humbucking pickups filter out higher frequencies because the two pickup coils are relatively close together. That is partly why humbuckers have a more mellow sound with less high end than single coil pickups -- the higher harmonics are canceling. The Stratocaster® sound is produced by a different spacing of the pickups. The coils can even be connected “out of phase” to produce an entirely different sound.

Magnet Type

There are many types of magnets in common use. Ceramic magnets are inexpensive, but brittle and do not produce a very strong field. These are commonly used in crafts and as refrigerator door magnets.

Other common types of magnets are:

- aluminum nickel cobalt [AlNiCo] (inexpensive)
- samarium cobalt (strong but expensive)
- neodymium boron iron (strongest and expensive)

There are some trade offs involved in pickup design. First, a stronger magnet means fewer turns of wire are needed for a certain audio output so that the pickup can be smaller. If the pickup is made in some standard size, a stronger magnet produces more audio output.

However, the stronger magnet types are much more expensive. That's why most pickups use less expensive AlNiCo magnets. Also, stronger magnets are not the cure-all for electric guitar. Since guitar strings are ferromagnetic and are attracted to the magnets, the pickups can affect the vibrations of the strings, which is bad since the pickups are only there to sense the vibrations, not change them.

Designer Sounds

When considering all the variations on pickup construction (magnet type, magnet position, magnet strength, wire size, number of turns on the coil, pickup position in the guitar), it is apparent that a nearly infinite variety of sounds are available. The first electric guitarists built their own pickups, and some aficionados still do.

(The above was adapted from “How do guitar pick-ups work?” By Hank Wallace available at <http://www.aqdi.com/pickups.htm>. Some of the basic physics in the original document is incorrect, but it contains a lot of information and is quite readable.)

Answers to Questions:

Please contact cipt_contact@cornell.edu to request the answers.

References:

How do guitar pick-ups works? By Hank Wallace (website)

<http://www.aqdi.com/pickups.htm>

Smith, Monica. 2001. “The Electric Guitar: How we got from Andres Segovia to Kurt Coban”. Invention and Technology, Summer 2001, Volume 20, Issue 1 (online article)

http://www.americanheritage.com/articles/magazine/it/2004/1/2004_1_12.shtml

The Guitar by Sam Hokin (website)

<http://www.bsharp.org/physics/stuff/guitar.html>

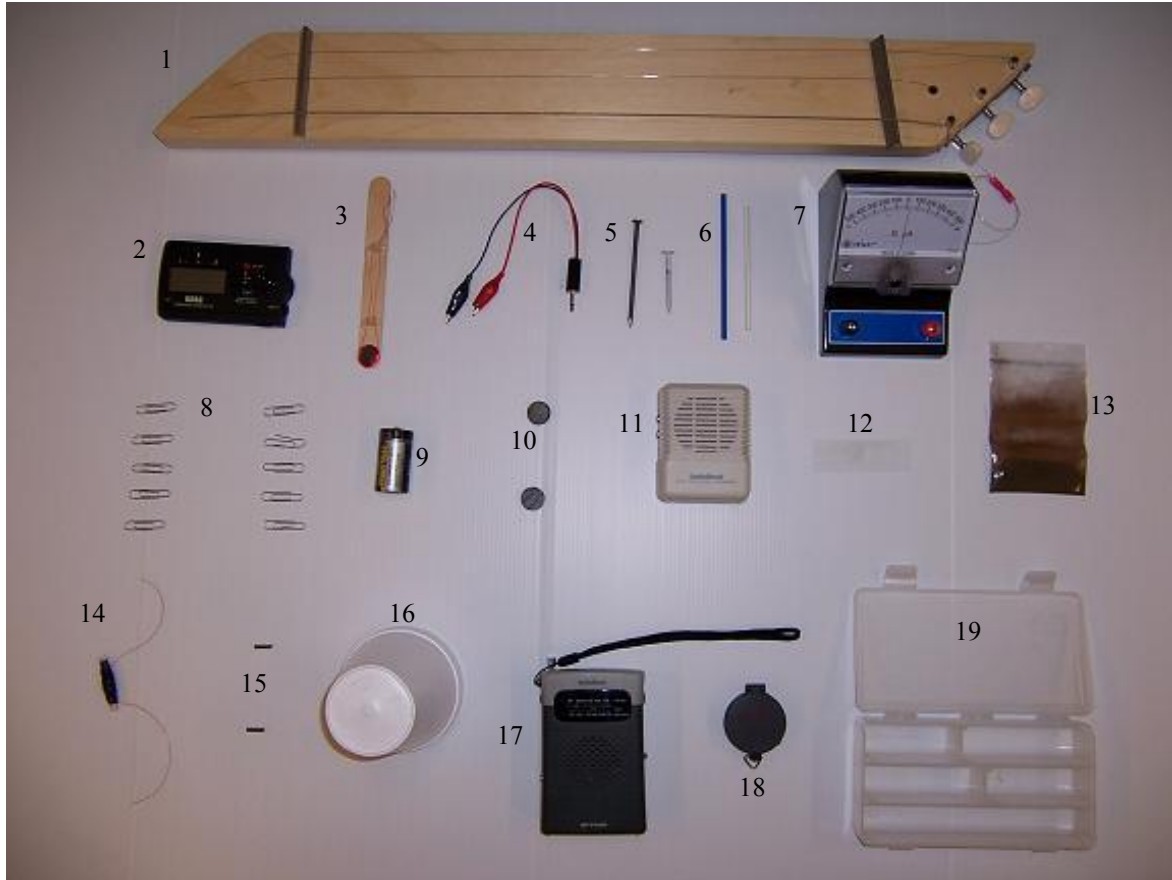
Physics of the Acoustic Guitar by Ian Billington (website)

<http://ffden-2.phys.uaf.edu/211.web.stuff/billington/main.htm>

How does a guitar work? By Joe Wolfe, University of South Wales, Department of Physics, Sydney, Australia (website)

<http://www.phys.unsw.edu.au/~jw/guitarintro.html>

Equipment



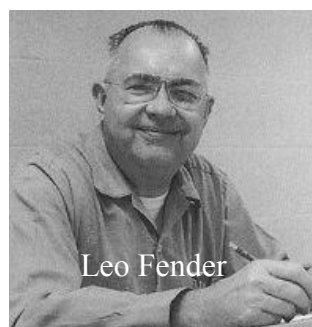
Item Number	Quantity	Item
1	1	Guitar
2	1	Tuner
3	1	“Pick-up Stick”
4	1	Connector, mono plug to alligator
5	1	Iron nail and aluminum nail
6	1	Paper stick and plastic stick
7	1	Galvanometer +/- 500 μ A
8	10	Paperclip
9	1	C cell battery
10	2	Ceramic magnet (1/2”)
11	1	Amplified speaker
12	1	Microscope slide
13	1	Iron filings
14	1	Plastic straw coiled with copper
15	2	Neodymium magnet (1/8”)
16	1	Styrofoam cup
17	1	Pocket radio
18	1	Compass
19	1	Storage box
20	1	(Not pictured) Auto speaker (4”)

Physics on an Electric Guitar

Electromagnetic Induction is the process of using magnetic fields to produce voltage, and in a complete circuit, a current. Michael Faraday first discovered it, using some of the works of Hans Christian Oersted. His work started at first using different combinations of wires and magnetic strengths and currents, but it wasn't until he tried moving the wires that he got any success. It turns out that electromagnetic induction is created by just that - the moving of a conductive substance through a magnetic field (or the moving of a magnetic field past a conductor).

An obvious use for electromagnetic induction is to generate electrical power. Any device that does this is known as a generator. Most generators work with a small loop of wire inside a magnetic field, oriented so that it may spin and move the wire through the magnetic field lines. This wire is connected to a turbine or some other spinning wheel, which is driven by steam, moving water, wind, or some other source of energy.

Electric guitars also make use of Faraday's discovery. Pick-up coils, consisting of a small magnet wound with wire, allow a stringed instrument to be "electrified" and amplify its sound output. Credit for the discovery/invention of the electric guitar is somewhat controversial, but most historians give credit to Leo Fender in the 1940's. In this lab you will learn how a pick-up coil works and use a home-make pick-up to play the "physics guitar."



Procedure:

I. What does electricity have to do with magnetism?

1. Take a 2 m length of magnet wire and wrap it around a short length of drinking straw. Leave 1-2 cm on each end of the straw without any wire. Leave 5 cm of magnet wire at the beginning and end. See illustration A.

(Note: A small piece of cellophane tape may be used to help hold magnet wire on the straw.)

2. Remove the enamel coating from the two wire ends.
3. Place the compass next to the coil.
4. Connect the two bare wires to the + and - terminals of a C cell battery and observe what happens to the compass needle.
5. Use the compass to explore the magnetic field around the coil.

Answer related questions on the student data sheet.

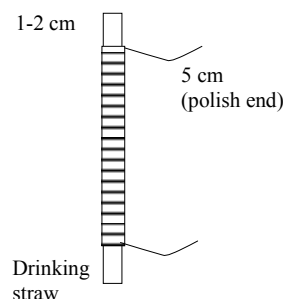


Illustration A

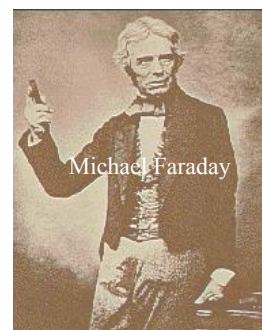
II. How strong is an electromagnet?

1. Without connecting the coil to the battery, see how many paperclips the coil can pick up.
2. Connect the coil to the 1.5 V battery and see how many paperclips you can pick up.
3. Take an iron nail and see how many paperclips you can pick up.
4. Slide the iron nail into the straw and connect the battery to the coil. See how many paperclips the coil can pick up.
5. Repeat Step #3-4 using an aluminum nail, paper stick and a plastic stick.

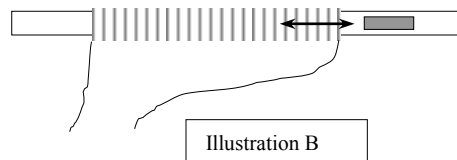
Answer related questions on the student data sheet.

III. What did Faraday tell us?

Faraday's Law of Induction states that *a changing magnetic field causes an electric field to be set up in a nearby wire, causing a current to flow if the wire is part of a closed circuit (a loop of wire for example).*



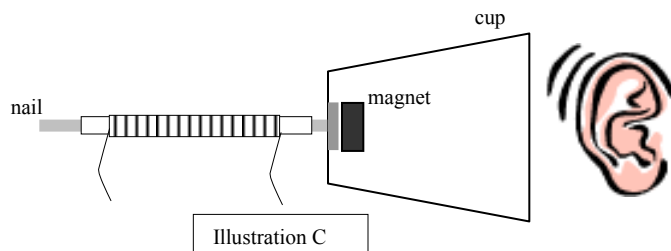
1. Attach the wires of the coil to a galvanometer.
2. Place a 1/8" diameter rod magnet in the straw/coil. With your fingers covering the two ends of the straw, move the straw so the magnet slides back-and-forth in the straw and watch the effect on the galvanometer. See illustration B.
3. Insert the magnet into the coil more slowly and observe the effect.
4. Connect the coil wires to the small speaker-amplifier using the mono-to-alligator adapter. Repeat step #2 and observe the effect.



Answer the appropriate questions on the student data sheet.

IV. Simply speaking

1. Push the iron nail through the bottom of a Styrofoam cup until the head is at the bottom. Place a small ceramic disk magnet on the head as pictured in the illustration to the right. (Refer to Illustration C.)
2. Slide your straw coil over the nail as pictured in the illustration to the right. (Refer to Illustration C.)
3. Find a strong station on a portable radio. Connect the coil to the earphone jack on the radio using the mono-to-alligator adapter and observe the results.



Answer the appropriate questions on the student data sheet.

V. Talking back to the speaker

1. Study Illustration D to the right and find the components we have discussed to this point: the coil and the magnet.
2. *Answer the appropriate questions on the student data sheet.*
3. Connect the small speaker-amplifier to the small speaker using the mono-to-alligator adapter. **VERY GENTLY** tap the speaker and observe the effect.
4. Using the same set-up, talk into the speaker as if it were a microphone. Observe the effect on the small amplifier.

Answer the appropriate questions on the student data sheet.

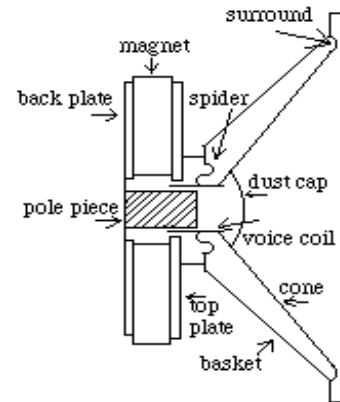


Illustration D

VI. The making of a magnet

1. Use the compass to detect the location of N and S poles on a ceramic disk magnet. Place one or two disk magnets with N poles up under a glass microscope slide (see Illustration E).
2. Sprinkle a small amount of iron filings on the top of the slide, tap it gently and observe the magnetic field lines shown in the filings.
3. Lay a guitar string across the flat side of one magnet.
4. Sprinkle a small amount of iron filings on a sheet of paper. Lay the guitar string in the filings, tap it a few times, pull it out and observe the results.
5. Use the compass to detect the location of N and S poles on the guitar string.

Answer the appropriate questions on the student data sheet.



Illustration E

VII. Electric guitar pick-up

1. Attach two wires on the electric “pick-up stick” (Illustration F) to the small speaker-amplifier using the mono-to-alligator adapter.
2. Turn the amplifier to the on position and turn the volume knob to maximum.
3. Slide the “pick-up stick” magnet under one of the strings in the region close to the bridge on The Physics Guitar. Make sure the magnet does not touch the string.
4. Pluck the string. Move the magnet in and out from under the string while it is vibrating and observe what happens.

Answer the appropriate questions on the student data sheet.



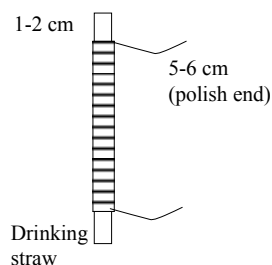
Illustration F

Physics on the Guitar

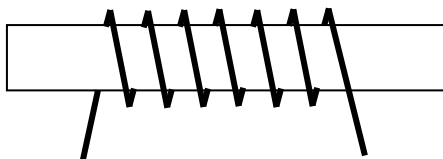
Student Data Sheet

I. What does electricity have to do with magnetism?

1. Describe the effect on the compass when a current passes through the coil.
2. Using the compass reading, label the north and south end of your straw coil.



3. On the diagram of the coil below, indicate the direction of the current flowing in the coil and the direction of the magnetic field caused by the current.

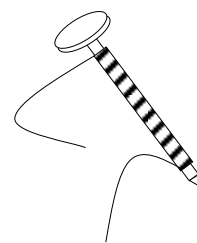


4. If you reversed the poles (+/-) by flipping the battery what happens to what you observe on the compass. Why?
5. Define “electromagnet” in your own words.

II. How strong is an electromagnet?

- a. Fill-in the following table relative to the number of paperclips.

In the straw coil	Number of paperclips picked up
Nothing	
Iron nail	
Paper stick	
Plastic stick	



- b. When were you able to pick up the most paperclips with the iron nail, in or out of the coil?
- c. Some materials become “magnetized” when exposed to a magnetic field—in other words they become a magnet. Which materials were magnetized by the electromagnet?

- d. Why do you think electromagnets often have iron cores?

III. What did Faraday tell us?

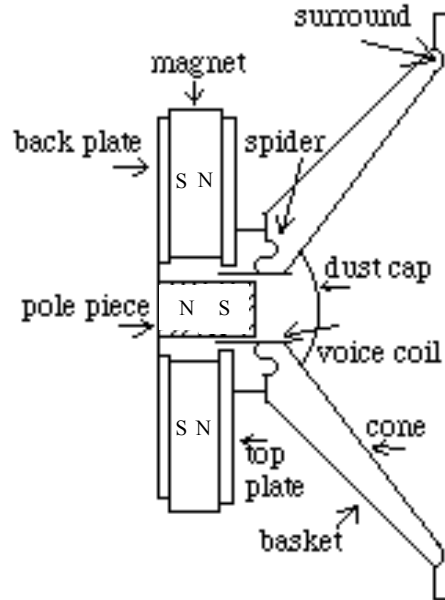
1. What does a galvanometer measure?
2. What happened to the current when the magnet entered the coil?
3. What happens to the current if you flip the poles of the magnet and put it in the coil?
4. How did changing the speed of the magnet affect the current?
5. What happens to the current when the magnet is not moving?
6. Write Faraday's Law in your own words.

IV. Simply Speaking

1. Were you able to hear the radio station from the simple speaker? What was vibrating to produce the sound?
2. The magnet on the head of the iron nail magnetized the nail. What caused the magnetized nail to move?
3. The earphone jack of the radio produces a changing electrical current that encodes the signal from the radio station. What was the purpose of plugging the coil into the earphone jack?
4. In your own words, describe how the simple speaker works.

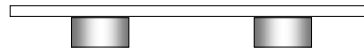
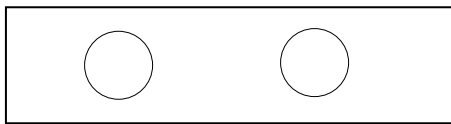
V. Talking back to the speaker

1. Circle the coil, the magnet, and all magnetized materials (including plates and pole piece) in the illustration to the right.
2. What you talk into the speaker and vibrate the cone, what happens to the voice coil?
3. How does the motion of the voice coil produce an electrical signal that can be heard with an amplifier?

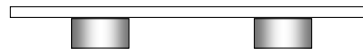


VI. The making of a magnet

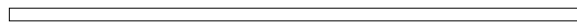
1. Draw a top view and side view illustration of your observation when you sprinkled the iron filings on to the slide below.



2. Draw a top view and side view of the magnetic field lines of the magnets. Label N and S poles.



3. Describe the effect of touching the guitar string to the iron filings after holding it close to the magnet. Did the guitar string get magnetized?
4. Draw the magnetic field of the guitar string, based on your observation of the iron filings. Label N and S poles.



VII. Electric guitar pick-up

1. On the diagram of the pickup coil below, draw the magnetic field lines of the magnet inside the coil.



2. What is the purpose of the magnet inside the pickup coil?
3. The magnet inside the pick-up coil is not moving--why does the coil still get a signal?
4. Why won't acoustic guitar strings work on an electric guitar?
5. **See what you have learned.** Study the illustration below of the magnetic pick-up with a guitar string positioned above it. Use this illustration to describe how a vibrating guitar string creates current in the pick-up coil, which can be turned into sound at a speaker. As part of your explanation, do the following:
 - Indicate the location of the N-S poles in the string
 - Draw the magnetic field lines for both the string and the pick-up
 - In your explanation, use the following terms: *magnetic field*, *magnetize*, *current*, and *Faraday's Law*.

